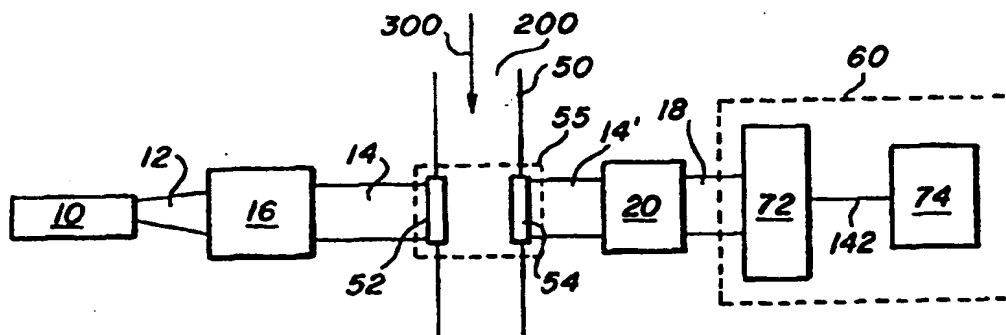




## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : <b>G01N 15/02, 15/06</b>	<b>A1</b>	(11) International Publication Number: <b>WO 95/12118</b> (43) International Publication Date: <b>4 May 1995 (04.05.95)</b>
<p>(21) International Application Number: <b>PCT/US94/12640</b></p> <p>(22) International Filing Date: <b>31 October 1994 (31.10.94)</b></p> <p>(30) Priority Data: <b>08/143,370</b>      <b>29 October 1993 (29.10.93)</b>      <b>US</b></p> <p>(71) Applicant: <b>THE GOVERNMENT OF THE UNITED STATES OF AMERICA</b>, as represented by <b>THE SECRETARY OF THE NAVY [US/US]</b>; Naval Research Laboratory, Code 3008.2, Washington, DC 20375-5325 (US).</p> <p>(72) Inventors: <b>REINTJES, John, F.</b>; 6019 Craft Road, Alexandria, VA 22310 (US). <b>DUNCAN, Michael, D.</b>; 3312 Bellview Avenue, Cheverly, MD 20785 (US). <b>MAHON, Rita</b>; 12515 Meadowood Drive, Silver Spring, MD 20904 (US). <b>TANKERSLEY, Lawrence, L.</b>; 94 Dewey Drive, Annapolis, MD 21401 (US). <b>HOWARD, Paul, L.</b>; 1212 Clearbrook Road, West Chester, PA 19380 (US). <b>CHAMBERLAIN, Martin</b>; 2200 Columbia Pike, Arlington, VA 22204 (US). <b>McKENNA, Thomas</b>; 800 N. Quincy Street, Arlington, VA 22215 (US).</p> <p>(74) Agent: <b>MCDONNELL, Thomas, E.</b>; Naval Research Laboratory, Code 3008.2, Washington, DC 20375-5325 (US).</p>	<p>(81) Designated States: <b>AU, CA, FI, JP, KR, NO, RU</b>, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).</p> <p><b>Published</b> <i>With international search report.</i></p>	

(54) Title: REAL TIME SUSPENDED PARTICLE MONITOR



## (57) Abstract

A method and apparatus for real-time monitoring of particulates in a fluid (200). The fluid (200) is illuminated by illuminating system (10, 16), and an image (202, 204, 212, 214) formed of the interior of the fluid (200). The image (202, 204, 212, 214) is then detected by a detecting system (20, 72, 74), and processed to determine the size, shape, etc. of particulates within the fluid (200).

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**REAL TIME SUSPENDED PARTICLE MONITOR****BACKGROUND OF THE INVENTION****1 Field of the Invention**

2 This invention relates to a fluid monitoring apparatus  
3 for detecting the presence of and determining the  
4 characteristics of particulate matter suspended in a fluid.  
5 More specifically, this invention relates to a device for the  
6 real time identification of the size and shape of a particle  
7 within a fluid by forming an optical image of the fluid and  
8 analyzing the image.

**9 Description of the Related Art**

10 Determination of the quantity, characteristics, and types  
11 of particulate matter in fluids is important for many  
12 applications such as monitoring fluids in engines and rotating  
13 machinery, industrial quality control, food processing,  
14 medical analysis, and observing environmental controls.  
15 Current devices for monitoring particulate matter in fluids  
16 involve various mechanical, electrical, or optical means.

17 Purely mechanical means involve collecting particulate  
18 matter in suitable traps such as filters, screens, or magnetic  
19 plugs. Analysis of the particles is done by removing the  
20 traps and examining the collected matter. These devices do  
21 not provide for real time monitoring. Electrical based  
22 particle monitoring devices are based upon induced currents.  
23 By sensing or measuring the change in an electric current, the  
24 concentration of electrically conducting or nonconducting  
25 particles can be determined. However, this technique is not  
26 able to identify the size or shape of the particles. In

1 conventional electrical-mechanical devices, such as electric  
2 chip detectors in engines, only electrically conducting  
3 particles are detected and the detectors provide no  
4 identification on the size or shape of the particles.

5 Optical devices have been used to determine the  
6 concentration, number, or size of particles. However, these  
7 devices are limited in their ability to identify the shape of  
8 particles. They identify the shape of particles by  
9 differentiation based on the degree of sphericity (or  
10 asymmetry) of the particles. Such devices illuminate a fluid  
11 sample and measure the intensity of the light scattered and/or  
12 transmitted at various detectors surrounding the sample. By  
13 comparing the intensity measured at the various detectors, a  
14 degree of sphericity or an asymmetry factor for the particle  
15 is determined. The particles are grouped by this degree of  
16 asphericity rather than identified or classified by the shape  
17 of the particle.

18 Similarly, the size of the particles is obtained by  
19 comparing the average intensity with a reference intensity or  
20 with the difference in intensity for a number of particles  
21 with a similar asphericity over time. This method yields  
22 information on the size of particles but does not provide real  
23 time size and shape identification.

24 Additionally, optical devices are subject to operating  
25 requirements that limit the number and type of applications  
26 for which they can be used. One such requirement is that the  
27 particles be passed one at a time or that the fluid be passed  
28 in a small volume through a specific point because the light

1 illuminating the particles is directed to that specific point.  
2 Additionally, in monitors that simply measure the light  
3 scattered from a single particle, the determination of  
4 symmetry is based upon the distribution of light scattered  
5 from a single particle. In such monitors, the symmetry of a  
6 particle cannot be accurately determined if two or more  
7 particles are illuminated at the same time. These  
8 requirements limit the application to those in which either  
9 the position of the particle is known and controlled or only a  
10 small sample of the fluid volume is passed to a monitor.

11 Another limitation of optical devices results from their  
12 sensitivity to air bubbles within the fluid. Entrained air  
13 bubbles are only distinguished from other particles by the  
14 high degree of sphericity or symmetry of the air bubbles. To  
15 remedy this, some devices must be oriented so that the air  
16 bubbles float to the top or upper area of the chamber  
17 containing the sample and, therefore, are removed from the  
18 sensing area of the fluid. Other devices will account for air  
19 bubbles by ignoring all highly spherical particles in any  
20 analysis of particulate matter.

21 Real time human visual inspection of particles can be  
22 accomplished by providing a window through which an individual  
23 can view the fluid. However, this method is limited to fluids  
24 flowing at low rates of speed. While using a strobe lamp or  
25 pulsed light to create the visual effect of stopping the  
26 motion of the particles will allow visual inspections for  
27 fluids flowing at higher speeds, these increased speeds are  
28 far below those encountered in many applications, for example,

1 the speed at which oil flows in aircraft engines.  
2 Additionally, visual inspection is limited to those  
3 applications in which the particles are of sufficient size to  
4 be viewed by an individual and to those applications in which  
5 the fluid is sufficiently transmissive to light of wavelengths  
6 which can be seen by humans.

7 An optical device which forms an image of the fluid would  
8 be advantageous because it would be able to combine the  
9 advantages of visual inspection with the advantages of optical  
10 devices. More specifically, by analyzing the image formed, an  
11 accurate and real time determination of the size and shape of  
12 particles within the fluid can be accomplished. Additionally,  
13 devices which are sensitive to a wide range of particle sizes  
14 and wavelengths of light can be made.

15 The need for a device and method which can identify the  
16 size and shape particulate matter within a fluid becomes  
17 readily apparent when one considers the problem of monitoring  
18 for particulate debris in the oil of helicopter or other  
19 aircraft. Particulate debris in helicopter or other aircraft  
20 engines can cause engine failure and loss of life. As a  
21 helicopter engine ages, particles from the engine or gear box  
22 components (bearings and gears) tend to flake off into the  
23 engine's oil. The size, shape, and density of flakes, as well  
24 as other types of debris, in the oil are indicative of engine  
25 condition, and can indicate when engine failure is imminent.  
26 Currently, magnetic plugs are removed for visual inspection of  
27 debris to spot upcoming engine failure. However, this must be  
28 done frequently to ensure that no failures occur. This

1 routine maintenance is costly, time consuming and often  
2 unnecessary. An oil debris monitoring system that provides  
3 real time information on the size and shape of particles  
4 within the oil will provide an early warning system for engine  
5 failure and can be used to record engine condition to identify  
6 when maintenance is needed. Thus, a system that can monitor  
7 size, shape, and density of particulate debris in engine oil  
8 in real time would be a welcome addition to the art.

#### 9 SUMMARY OF THE INVENTION

10 It is an object of this invention to provide a system and  
11 method of using the system, for the real time monitoring of  
12 suspended particulate matter in a fluid that is capable of  
13 accurately identifying the size and shape of particles within  
14 a fluid.

15 Another object of the present invention is the provision  
16 of a system which will form and analyze an image of a fluid to  
17 accurately determine the size and shape of particles within  
18 the fluid.

19 A further object of the present invention is the  
20 provision of a system that accurately determines the size and  
21 shape of particles within a fluid, while distinguishing  
22 suspended particles from entrained air bubbles.

23 Another object of this invention is to provide a system  
24 which will accurately determine the size and shape of  
25 particles, even in the presence of a rapidly flowing fluid by  
26 using one or more pulsed light sources to allow imaging with a  
27 desired degree of spatial resolution.

28 Another object of this invention is to provide a system

1 which can monitor a large volume of fluid without the need to  
2 know or control the position of particles in fluid.

3 Yet a further object of this invention is to provide a  
4 system which uses parallel processing, of which a neural  
5 network is an example, to analyze an image of a fluid volume  
6 to quickly and accurately identify and classify particle  
7 shapes within the fluid.

8 In accordance with these and other objects made apparent  
9 hereinafter, the invention concerns an method and apparatus  
10 for the real time monitoring of suspended particulates in a  
11 fluid in which the apparatus uses a pulsed light source and  
12 collimating optics to direct an optical beam into a fluid  
13 chamber through which is passing a fluid to be examined. An  
14 optical image of the fluid within the fluid chamber is formed  
15 responsive to the light, and the image detected. The detected  
16 image contains the necessary information to permit  
17 classification of particulates in the fluid according to  
18 shape, size, etc. Preferably, the image is analyzed in situ by  
19 dedicated hardware pre-programmed to the task.

#### 20 BRIEF DESCRIPTION OF THE DRAWINGS

21 These and other objects, features and advantages of the  
22 invention will become better understood by reference to the  
23 following detailed description when considered in connection  
24 with the accompanying drawings wherein like reference numerals  
25 designate identical or corresponding parts throughout the  
26 several views and wherein:

27 FIG. 1 is a schematic diagram illustrating a first  
28 embodiment of the present invention;



FIGS. 5A and 5B show examples of images of the center of a fluid chamber.

## DETAILED DESCRIPTION

Referring now to Fig. 1, there is shown a first embodiment of the present invention. In Fig 1, a fluid 200 to be monitored passes through fluid chamber 55. Fluid 200, either a liquid or a gas, flows in the direction from top to bottom of the sheet in Fig. 1, as indicated by reference arrow 300. Source 10 emits optical beam 12 into collimating optics 16. Optical beam 12 from source 10 can be either coherent or noncoherent, depending on the operation and application of the embodiment. Additionally, source 10 can emit beam 12 directly into collimating optics 16 (as shown in Fig. 1) or source 10 can be located some distance away with optical beam 12 directed to collimating optics 16 by conventional means, such as fiber optic cable. Collimating optics 16 produce a collimated beam 14 which illuminates fluid chamber 55. Collimated beam 14 preferably has an area such that the entire length, in the direction of the flow of the fluid, of fluid chamber 55 and the entire width, in the direction orthogonal to the sheet in Fig. 1, of fluid chamber 55 is illuminated. The collimation can be accomplished by any of several conventional means including, but not limited to, a lens, a

1 mirror, or a lens and mirror combination. The collimating  
2 optics can also include optics for folding the beam to allow  
3 the source to be located physically adjacent to the fluid  
4 column 50.

5 Collimated beam 14, propagating in a direction from  
6 source 10 toward detector 72, enters fluid chamber 55 such  
7 that beam 72 is transverse to, and preferably orthogonal to,  
8 the flow of fluid 200. Fluid chamber 55 has a light  
9 transmitting portion 52 allowing collimated beam 14 to enter  
10 the fluid chamber and a second light transmitting portion 54  
11 allowing optical beam 14' (the portion of collimated beam 14  
12 transmitted through fluid 200) to exit fluid chamber 55.  
13 Light transmitting portions 52 and 54 bounding fluid chamber  
14 55 should be of sufficient optical quality to allow imaging at  
15 the desired degree of spatial resolution.

16 Imaging system 20 uses optical beam 14' exiting fluid  
17 chamber 55 to form an image of fluid 200 within fluid chamber  
18 55. The image formed by imaging system 20 is carried to  
19 optical detector 72 in optical beam 18. Optical detector 72  
20 is an optically sensitive surface with two dimensional spatial  
21 resolution. The output of detector 72 is connected to shape  
22 classifier 74. Detector 72 converts the image formed on the  
23 optically sensitive surface into electronic data. This data  
24 is transferred to shape classifier 74 which analyzes the  
25 output data of detector 72 and identifies the size and shape  
26 of a particle in two dimensions based on characteristic  
27 patterns (straight lines, corners, curves, etc.). Together,  
28 optical detector 72 and shape classifier 74 form image

processor 60. Both optical detector 72 and shape classifier 74 can be located some distance from fluid chamber 55 with the image carried to the image processor by conventional means, such as fiber optic cable. A complete description of the operation of image processor 60 is discussed below in reference to Figs. 4A and 4B.

In operation, source 10 is pulsed so a "stop action" image of fluid 200 flowing within chamber 55 can be created. With each pulse, a new image of fluid 200 within fluid chamber 55 is created onto optical detector 72. Typically, in the time between pulses, the image is analyzed to determine the size and shape of the particles present in the fluid. The pulse duration and the pulse repetition rate are chosen with regard to the flow speed of fluid 200. The duration of the pulse should be short enough so that during the pulse the particles do not move by more than the desired spatial resolution. For example, oil flowing through an aircraft engine will flow through a fluid chamber at a maximum rate of 10 m/s. If the desired spatial resolution is 10 microns, the pulse duration should be 1  $\mu$ s. The repetition rate is set so that, in the time between pulses, fluid 200 travels a distance equal to the length, in the direction of fluid flow, of the fluid imaged, thereby monitoring all the fluid passing through the chamber. For example, referring to the oil flowing in an aircraft engine, if the length of oil imaged is 1 cm, the time between pulses should be 1 ms (the time it takes the oil moving at 10 m/s to travel 1 cm). However, the repetition rate can be increased to allow the fluid to be imaged more

1     than once as the fluid passes through the fluid chamber.  
2     Additionally, source 10 must emit optical beam 12 with a  
3     wavelength such that the beam can be transmitted through fluid  
4     200 in sufficient quantity to be detectable yet at the same  
5     time be absorbed by the particulate matter within the fluid.  
6     For illuminating the oil used in aircraft engines, the  
7     wavelength of source 10 should be greater than 800-nm to allow  
8     a sufficient quantity of light to be transmitted through the  
9     oil, with a preferred wavelength being between 850 and 1000-  
10    nm. A single-mode diode laser with a wavelength of 850-nm can  
11    be used to illuminate the oil used in aircraft engines,  
12    although any source emitting light with the proper wavelength  
13    that is also capable of being pulsed at the proper repetition  
14    and duration rates can be used.

15       Shape classifier 74 can operate with any of a large  
16    number of known techniques to classify particulate shape, such  
17    as the techniques commonly used for character identification,  
18    adapted to specific particulate shapes of interest. Examples  
19    of such techniques are: template matching, e.g. two  
20    dimensional correlation between the image and a template  
21    image; or production of a spatial Fourier transform of the  
22    image, and comparison with a template spectrum. One could  
23    also use neural net classifiers, with any commonly used  
24    classification techniques used with such neural nets, e.g. use  
25    of radial basis function networks, mutual perceptrons with back  
26    propagation, or apadtive resonance theory.

27       When forming the image of fluid 200 onto optical detector  
28    72, the image plane will be at the entrance face of the

1 optical detector, while the object plane will be set based  
2 upon the position of the particles. If the position of the  
3 particles in fluid 200 within fluid chamber 55 is known or  
4 controlled, such as with a narrow fluid chamber, that known  
5 position can be used as the object plane by the imaging  
6 system. Additionally, when the position of the particles is  
7 known or controlled such that the particles will always be in  
8 the object plane, either coherent or noncoherent light can be  
9 used to illuminate the fluid. If the position of the  
10 particles is not known or controlled, imaging system 20 can  
11 form an image of fluid 200 using a plane at any position  
12 across fluid chamber 55 for the object plane. Preferably, the  
13 object plane will be at or near the center of fluid chamber 55  
14 so that the maximum distance from the object plane that  
15 particles may be located can be minimized. The distance is  
16 minimized because, the closer a particle is to the object  
17 plane, the better the resolution of the particle in the image.  
18 When the position of the particles is not known or controlled,  
19 a coherent light source is preferred. Coherent light is  
20 preferred because it increases the distance from the object  
21 plane that particles can be located and yet maintain their  
22 shape in an image of the fluid. The shape of the particle can  
23 be maintained in an image if coherent light is used and the  
24 diffraction pattern is characteristic of the optical near  
25 field. Therefore, the shape of a particle at any position  
26 across the fluid chamber will be maintained in the image of  
27 the fluid chamber if the fluid chamber is illuminated with  
28 coherent light and the diffraction pattern of the light.

1 exiting the fluid chamber is characteristic of the optical  
2 near field.

3 Imaging system 20 can form either a direct image of the  
4 fluid volume or its optical Fourier transform depending upon  
5 the requirements of the image processor 60. The imaging can  
6 be accomplished by any of several conventional means  
7 including, but not limited to, lenses, mirrors, or coherent  
8 optical fiber bundles (proximity focusing). If space is  
9 limited, imaging system 20 may use mirrors (not shown) to  
10 route beam 18 to gain the proper distance needed to focus the  
11 image of fluid chamber 55 onto optical detector 72.

12 The dimensions of fluid chamber 55 can be any size.  
13 However, as discussed above, it is preferable that width 302  
14 of fluid chamber 55 be such that the diffraction pattern of  
15 the light exiting the fluid chamber is characteristic of the  
16 optical near field. Additionally, in selecting length 304 of  
17 fluid chamber 55, and the width (in the direction orthogonal  
18 to the sheet in Fig. 1) of fluid chamber 55 consideration  
19 should be given to the expected size of the particles and the  
20 size of the image created.

21 Fig. 4A shows a preferred embodiment of image processor  
22 60. Optical beam 18 from the imaging system (not shown)  
23 carries the image of the fluid within the fluid chamber to  
24 optical detector 72. Optical detector 72 has an optically  
25 sensitive surface containing a two dimensional planar array of  
26 opto-electric converters 140 each of which constitutes an  
27 image pixel. Output 142 of detector 72 is connected to shape  
28 classifier 74 which analyzes the output of detector 72 and

1 identifies the size and shape of a particle in two dimensions  
2 based on characteristic patterns (straight lines, corners,  
3 curves, etc.).

4 In operation, optical detector 72 is illuminated by beam  
5 18 for each pulse by the source (as described above in  
6 reference to Fig. 1). Upon illumination of optical detector  
7 72 by beam 18, each opto-electric converter 140 creates  
8 electronic data proportional to the intensity of light from  
9 beam 18 received at the converter. Because the electronic  
10 data produced at each converter 140 is proportional to the  
11 intensity of the light received, variations in the intensity  
12 of the image are maintained in the electronic data. Thus, the  
13 optical image formed on the face of detector 72 is converted  
14 into electronic data that is capable of subsequent electronic  
15 reading and processing.

16 Because only the portion of the image which is formed on  
17 optical detector 72 will be converted into electrical signals,  
18 the dimensions of the image produced and the dimensions of  
19 detector 72 should correspond to each other. Additionally, to  
20 determine the size of a particle within the desired degree of  
21 spatial resolution, the distance between the centers of each  
22 image pixel (converter) 140 on optical detector 72 should be  
23 no larger than the unit of resolution. For instance, if the  
24 desired degree of spatial resolution is 10  $\mu\text{m}$ , the distance  
25 between the centers of any two horizontally or vertically  
26 adjacent pixels 140 should be less than or equal to 10- $\mu\text{m}$ .

27 Also, several optical detectors can be combined in an  
28 array to form a larger optical detector. This arrangement is

1 represented in Fig. 4A by the combination of optical detectors  
2 172, 174, and 176 along with optical detector 72 to form  
3 optical detector array 72'. The output of each individual  
4 detector (72, 172, 174, 176) in the array will be connected to  
5 shape classifier 74. Additionally, when several detectors are  
6 combined into this type of array, the image pixels located  
7 next to the edge of the detector should be sufficiently close  
8 to the edge of the detector such that the distance between the  
9 centers of two horizontally or vertically adjacent pixels on  
10 neighboring detectors is less than or equal to the desired  
11 spatial resolution.

12 Converter 140 in detector 72 can have an associated  
13 charge coupled device (CCD) element which receives a charge  
14 proportional to the intensity of light at the converter. The  
15 CCD element can be read to provide an output value  
16 corresponding to the charge received at the element. The CCD  
17 elements can be read serially providing at output 142 a single  
18 string of output values or the CCD's can be read in parallel  
19 such that all the CCD elements are read simultaneously  
20 providing a plurality of output 142 connections with each  
21 individual output 142 containing a single output value from a  
22 single CCD. Similarly, converter 140 in detector 72 can be a  
23 phototransistor. The phototransistor will produce a response,  
24 such as a current gain, proportional to the amount of light  
25 received. The size of the response produced by the  
26 phototransistor can be used to provide an output value  
27 corresponding to the intensity of light received at the  
28 phototransistor. Similarly, the output 142 from detector 72



1 comprised of phototransistors can be read serially or in  
2 parallel.

3 The output data from detector 72 is sent to shape  
4 classifier 74. Shape classifier 74 can process the output  
5 data from detector 72 using an appropriate pattern recognition  
6 or pattern matching technique, such as van der Lugt  
7 correlation or Bayesian classification, to determine the size  
8 and shape of particles in the fluid. The exact operation of  
9 shape classifier 74 will depend upon the type of pattern  
10 recognition or pattern matching algorithm chosen of which many  
11 types are currently known. Figure 4B shows an illustration of  
12 the embodiment of shape classifier 74.

13 In Figure 4B, shape classifier 74 performs a correlation  
14 algorithm, the shape classifier will typically contain a  
15 microprocessor 77 which will use the output data from detector  
16 72 along with information stored in memory means 78 to perform  
17 the correlation function. Optionally, the shape classifier  
18 can contain a preprocessor 76 the operation of which will be  
19 discussed below.

20 In operation, the image of the fluid is formed on the  
21 face of detector 72. The detector converts the optical image  
22 into electronic data as previously explained. The output data  
23 from detector 72 is sent to shape classifier 74. Preferably,  
24 the data is output in parallel, as shown in Fig 4B, over  
25 multiple output connections 142. Thus, electronic data  
26 representing an input image from detector 72 is received by  
27 shape classifier 74. Using the data for the input image  
28 obtained from detector 72 and data for reference images stored

in memory means 78, microprocessor 77 can perform a correlation algorithm, such as van der Lugt correlation.

Image correlation is based on the correlation theorem:

$$A_i(x,y) \otimes A_r(x,y) = F^{-1}[F(A_i(x,y))F^*(A_r(x,y))]$$

where  $A_i$  and  $A_r$  represent the input and reference images,  $\otimes$  denotes the operation of correlation,  $F$  denotes the Fourier transform, and  $*$  denotes the complex conjugate. Mathematical correlation of two images will produce a correlation value corresponding to the degree of similarity of the two images. Images of particles of roughly the same size and shape will result a high correlation product. By performing correlation of the input image with the reference images and determining which correlation product has the largest value, the size and shape of the particle can be determined.

To improve the performance of microprocessor 77, preprocessor 76 can be used. The preprocessor can be used to perform an intermediate transform, such as a Hough transform, to remove rotational and size dependence. By removing these dependencies, the number of reference images can be reduced thereby reducing the number of correlation products which must be produced. Additionally, preprocessor 76 can implement traditional image processing techniques to segment and find areas of the image where particles are represented and to delineate the boundary of such objects. By only passing the data from the input image which contains the image of a particle, the amount of data which is sent to microprocessor 77 for correlation is reduced. Similarly, preprocessor 76 can be used to identify certain types or classes of particles

1 which do not need to be identified by size and shape. For  
2 example, for the application of monitoring particles in the  
3 oil of aircraft engines, it is expected that the debris in the  
4 oil will be nonspherical. Therefore, it can be assumed that  
5 all round particles are entrained air bubbles. By using  
6 traditional image processing techniques, such as calculating  
7 the curvature around and image, data corresponding to round  
8 particles does not need to be processed by microprocessor 77.  
9 This will reduce the computational requirements of  
10 microprocessor 77 in systems where the number of bubbles  
11 greatly exceeds the number of particulates.

12 A second embodiment of the present invention is shown in  
13 Fig. 2. In the embodiment of Fig. 2, the characteristics,  
14 requirements, and operation of elements with reference  
15 numerals identical to those in Fig. 1 are the same as  
16 previously described in reference to Fig. 1.

17 In Fig. 2, source 10 provides an optical beam 12 to the  
18 collimating optics 16 which produces a collimated beam 14  
19 which is directed toward beam splitter 105. Beam splitter 105  
20 allows a portion of beam 14 to pass through and continue on in  
21 the direction toward fluid chamber 55 while reflecting a  
22 portion of beam 14 in a direction away from imaging system 20.  
23 The portion of beam 14 directed away from imaging system 20,  
24 is lost from the system. Collimated beam 14 which has passed  
25 through beam splitter 105 enters the fluid chamber 55 through  
26 window 52, propagates through fluid 200, and exits through  
27 window 54. After exiting fluid chamber 55, optical system 22  
28 focuses transmitted beam 14' into phase conjugate reflector

1     **100.**

2           Phase conjugate reflector 100 precisely changes the  
3     direction of propagation of the incident beam in such a way  
4     that the return beam retraces the same path as the incident  
5     beam. The return beam travels back through imaging system 22,  
6     entering fluid chamber 55 through window 54 and exiting  
7     through window 52. The return beam is then split by beam  
8     splitter 105 which directs a portion of the return beam toward  
9     imaging system 20 while allowing the remaining portion to pass  
10    through and continue in the same direction of propagation.  
11   Imaging system 20 forms either a direct image of the center of  
12   the fluid chamber or its optical Fourier transform, onto  
13   optical detector 72 of image processor 60.

14           As in the previous embodiment, light source 10 is pulsed  
15   so a "stop action" image of fluid 200 flowing through fluid  
16   chamber 55 is created at detector 72. Collimated beam 14'  
17   transmitted through the chamber is focused onto phase  
18   conjugate reflector 100 by optical system 22. Optical system  
19   22, which can be a lens, is used to capture beam 14' exiting  
20   fluid chamber 55 and focus beam 14' onto phase conjugate  
21   reflector 100. Optical system 22 is placed an arbitrary  
22   distance from window 54 or the imaging system can be  
23   incorporated into window 54. Phase conjugate reflector 100  
24   precisely changes the direction of propagation of the incident  
25   beam causing the return beam to follow the same path through  
26   imaging system 22 and fluid chamber 55 as the incident beam.  
27   After exiting fluid chamber 55, the return beam is directed to  
28   imaging system 20 which forms an image of an object plane

1 within fluid 200 onto optical detector 22 in image processor  
2 60. This image is then analyzed by image processor 60. Once  
3 again, a new image of fluid 200 within fluid chamber 55 will  
4 be created each time source 10 is pulsed, and therefore, the  
5 analysis should be completed in the time between pulses, or in  
6 the time between indications by preprocessor 76 that non  
7 spherical particulates occur in fluid 200. The operation of  
8 image processor 60 is as described above in reference to Figs.  
9 4A and 4B.

10 Fig. 5A shows an example of an image formed at the  
11 optical detector of the device described in reference to Fig.  
12 1. The image in Fig. 5A shows how an air bubble 202 and a  
13 nearly spherical particle 204 appear on the face of the  
14 optical detector. Air bubble 202 in the fluid appears in the  
15 image as a dark circle against a bright background due to the  
16 scattering of the light by the air bubble. Suspended particle  
17 204 also appears as a dark shadow against a bright background  
18 because the light is absorbed by the particle.

19 Fig. 5B, on the other hand, shows how the same image  
20 would appear on the optical detector of the embodiment  
21 described in Fig. 2. As can be seen in Fig. 5B, air bubble  
22 212 appears as a dark ring against a light background while  
23 the image of the suspended particle 214 remains a dark shadow.  
24 Thus, in an application where one expects to see spherical or  
25 very nearly spherical particles in the fluid, the embodiment  
26 of Fig. 2, allows the application to distinguish air bubbles  
27 from spherical particles.

28 A third embodiment of the present invention, shown in

Fig. 3, incorporates two of the devices described in reference to Fig. 1 around a single fluid chamber 55. Preferably, the devices 1 and 3 are combined in such a way that the two collimated beams 14 and 34 entering the fluid chamber are essentially orthogonal to each other, as well as to fluid chamber 55. In this embodiment shown in Fig. 3, the direction of the flow of the fluid (not shown) through the fluid chamber 55 can be either into or out of the sheet.

Sources 10 and 30 provide optical beams 12 and 32, respectively. The two optical beams 12 and 32 are collimated by collimating means 16 and 36, respectively. A first collimated beam 14 enters fluid chamber 55 through window 52, propagates through the fluid, and exits fluid chamber 55 through window 54. Imaging system 20 acts on collimated beam 14' that has passed through fluid chamber 55 to form an image with an object plane within fluid chamber 55 onto optical detector 72 of image processor 60. Simultaneously, a second collimated beam 34 enters the fluid chamber 55 through window 57, propagates through the fluid, and exits through window 59. Imaging system 40 acts on collimated beam 34' exiting fluid chamber 55 to form an image the fluid within fluid chamber 55 onto optical detector 72 of image processor 62.

The outputs of the image processors 60 and 62, containing information on the size, shape, and position of the particles in two dimensions, are combined together in shape processor 90 to obtain size and shape information for three dimensions. Shape processor 90 can be used to calculate simple information such as volume of the particle or it can be used to calculate

1 more complex information for three dimensions to further  
2 classify particle types such as flakes, crystallites or cubes.

3 In this embodiment, the characteristics, operation, and  
4 requirements of sources 10 and 30, collimating optics 16 and  
5 36, fluid chamber 55, windows 52, 54, 57, and 59, and imaging  
6 systems 20 and 40 are as previously described in reference to  
7 Fig. 1.

8 In operation, sources 10 and 30 are pulsed simultaneously  
9 with the pulse duration and pulse repetition rate chosen with  
10 regard to the flow speed of the fluid. The duration of the  
11 pulse should be short enough so that during the pulse the  
12 particles do not move by more than the desired spatial  
13 resolution. The repetition rate is set so that, in the time  
14 between pulses, the fluid travels a distance equal to the  
15 length, in the direction of fluid flow, of the fluid imaged.  
16 The wavelength of each source must be such that the light can  
17 be transmitted through the fluid in sufficient quantity to be  
18 detectable yet at the same time be absorbed by the particulate  
19 matter within the fluid. However, the wavelengths of the  
20 sources need not be identical.

21 The operation of image processors 60 and 62 is as  
22 described above in reference to Figs. 4A. Additionally, data  
23 from image processors 60 and 62, containing information on the  
24 size, shape, and position of the particles in two dimensions,  
25 should be combined together in a shape processor 90 to obtain  
26 size and shape information for three dimensions.

27 While the embodiment of the present invention shown in  
28 Fig. 3 combines two of the devices in Fig. 1 around a single

1 fluid chamber 55, it is also possible to combine three or more  
2 of the devices shown in Fig. 1 around a single fluid chamber  
3 to obtain more detailed information. Additionally, another  
4 variation can be had by combining two or more of the devices  
5 of Fig. 2 around a single fluid chamber.



1     What is claimed is:

2     1.     An apparatus for the real time monitoring of suspended  
3     particulates in a fluid, said apparatus comprising:

4             a pulsed light source;

5             means for collimating an optical beam from said  
6     light source;

7             a fluid chamber for passing a fluid to be examined,  
8     said fluid chamber being suitable for illumination by said  
9     collimated beam;

10            means for forming an optical image of the fluid  
11     within said fluid chamber; and

12            means for detecting said optical image.

13     2.     The apparatus of Claim 1 wherein said apparatus further  
14     comprises means for detecting, responsive to said means for  
15     detecting, shapes of said particulates in said fluid.

16     3.     A method for the real time monitoring of suspended  
17     particulate matter in a fluid, said method comprising the  
18     steps of:

19            a) illuminating a fluid;

20            b) forming an optical image of the illuminated  
21     fluid;

22            c) detecting an optical image of the fluid; and

23            d) analyzing an optical image of the fluid.

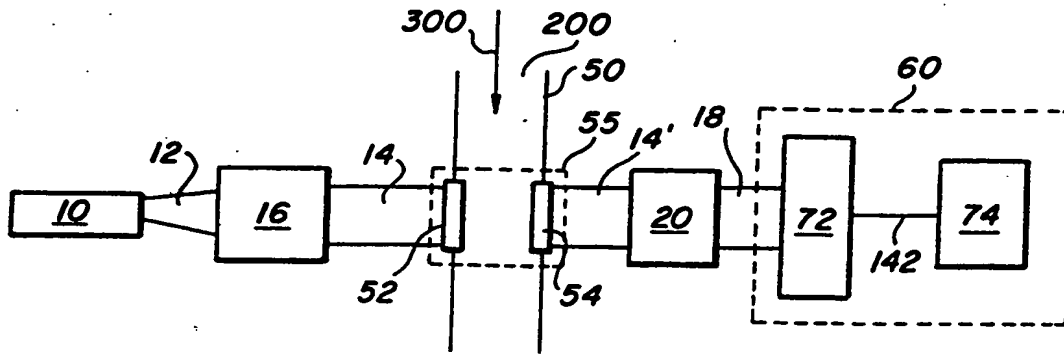


FIG. 1

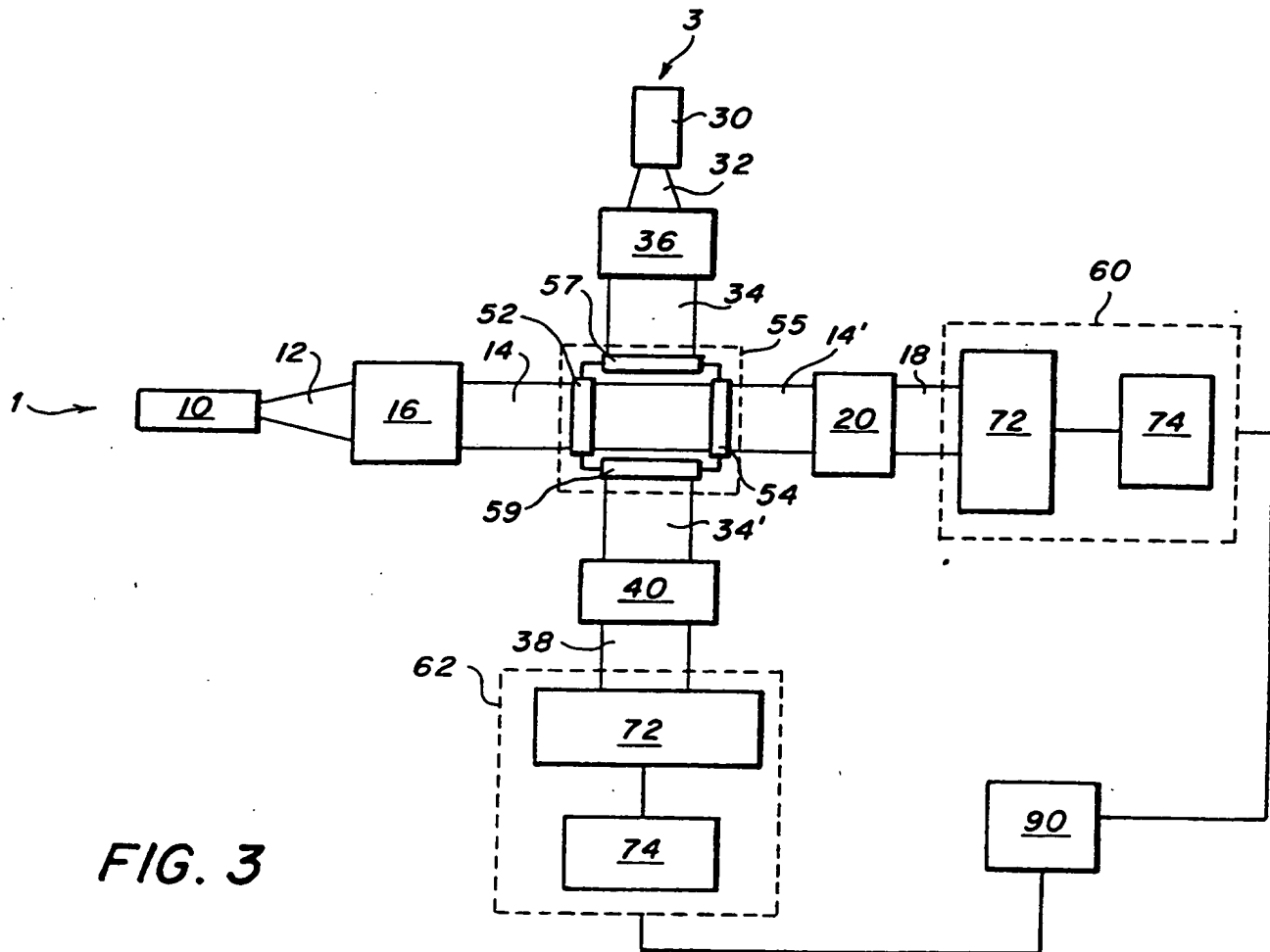


FIG. 3

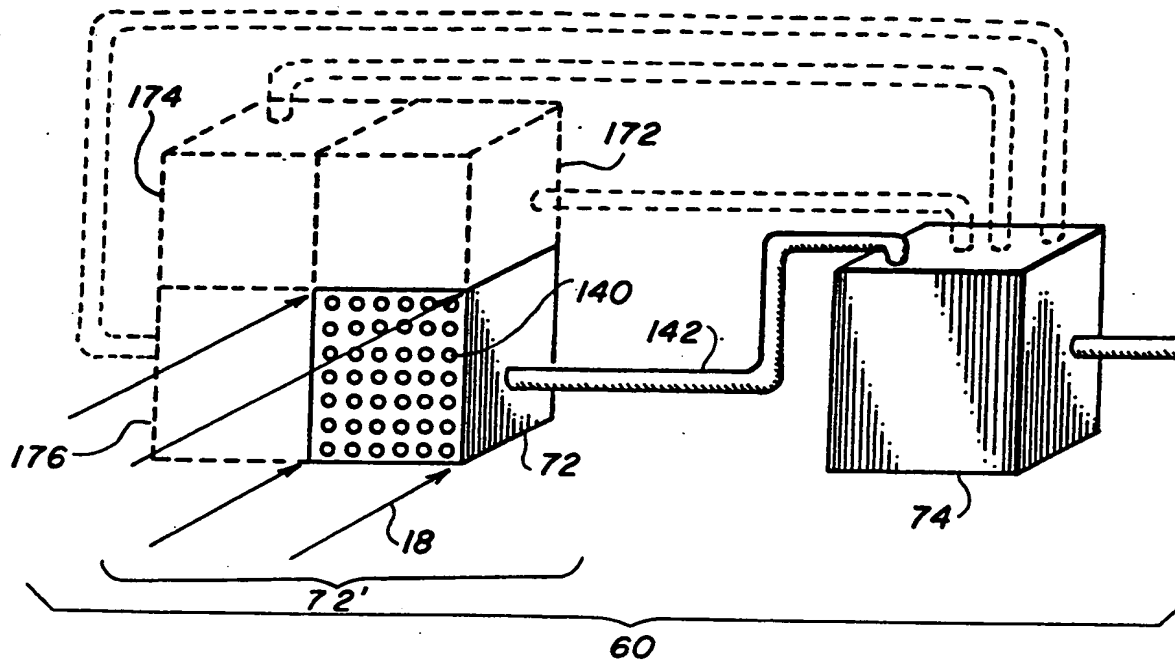


FIG. 4A

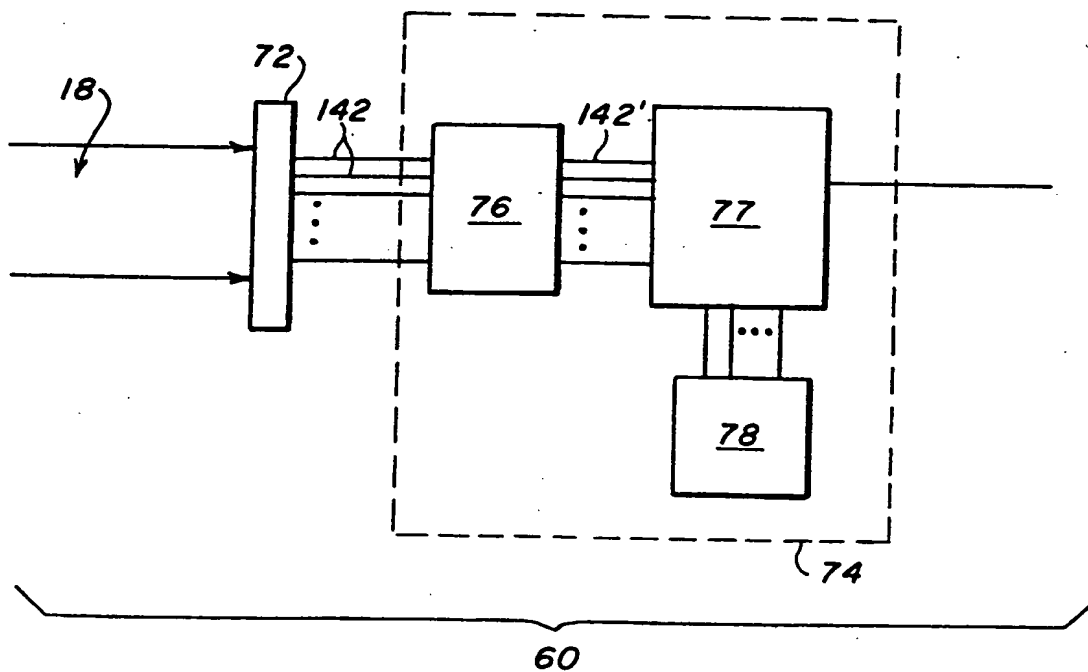


FIG. 4B

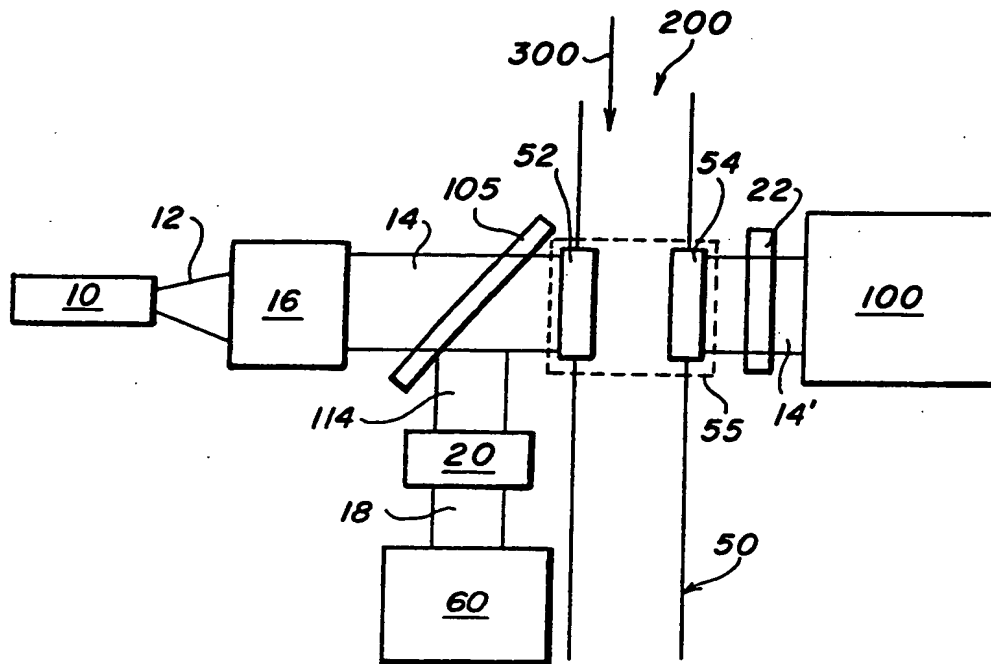


FIG. 2

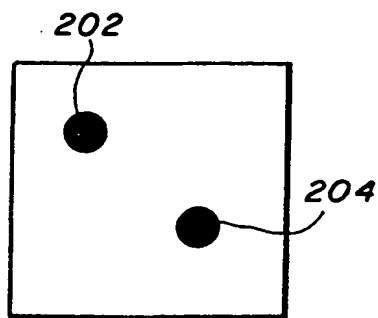


FIG. 5A

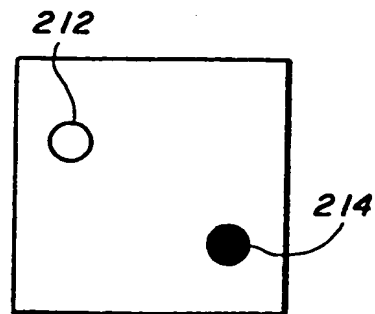


FIG. 5B

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : G01N 15/02, 15/06

US CL : 356/335, 336, 343; 250/574, 222.2

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/335, 336, 343; 250/574, 222.2

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 4,393,466 (DEINDOERFER ET AL) 12 July 1983, figure 4.	3
X	EP-0507746 (LONGOBARDI ET AL) 07 October 1992, figure 1.	3
X	JP-5045274 (KAMIWANO) 23 February 1993, figures 1-3 and 5a.	1-3
Y	US, A, 3,641,320 (STOCKHAM ET AL) 08 February 1972, figures 1 and 2.	1-2

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:		T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
*A	document defining the general state of the art which is not considered to be of particular relevance	X	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
*E	earlier document published on or after the international filing date	Y	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
*L	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	* &	document member of the same patent family
*O	document referring to an oral disclosure, use, exhibition or other means		
*P	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

04 JANUARY 1995

Date of mailing of the international search report

10 JAN 1995

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